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Simulating the effect of production lot sizes on material and energy efficiency

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Abstract

In the past, factory improvement measures have focused on cost optimization and agility increases, while neglecting the potential effects on material and energy efficiency. Production lot sizes, for example, have been determined solely with respect to cost and logistical performance. This paper presents a method to simulate material and energy efficiency in the factory as a function of lot size. Using the example of a plastics manufacturer, the simulation results reveal a gap between the lean optimum lot size and the material efficiency optimum.

Keywords: lot-sizing; material efficiency; energy efficiency; simulation;

1. Introduction and Motivation

While factory management improvement measures have a positive effect on logistical and cost metrics, they may have undesired effects on energy consumption and material efficiency, which negatively influence cost and ecological sustainability. This connection is evidenced by significant labor productivity gains in past decades, with only moderate gains in material and energy efficiency [1].

To find the balance between manufacturing cost and logistical performance, factories have employed a number of economic lot size calculations over the last century [2]. In the past 20 years, these calculations have been challenged by lean philosophy that favors smaller lot sizes over their larger, purely cost-minimized counterparts, due to the reduced capital lock-up and the ability to react quickly to changing customer needs [3]. Production lot size affects not only logistical and cost goals, but also energy consumption and material waste, and thereby the environment. Set-ups consume energy and consumable materials; therefore, the interruption to the production process can result in considerable startup losses [4]. On the other hand, inventory shrinkage due to rust formation, mold growth, or mechanical damage can occur as a result of large lots [5].

In order to determine the optimal production lot size from the environmental perspective, the research team developed a simulation-based method in the ultra-efficiency factory project funded by the state of Baden-Württemberg. This paper discusses the application of this simulation method at a plastics manufacturer to identify the ideal lot size for injection molding.

2. State of the Art

2.1. Optimal Lot Size Calculations

Historically, lot size calculations were purely cost-based, weighing the set-up costs (e.g. labor, machine depreciation), against inventory cost (e.g. warehousing, depreciation/capital lock-up) [6]. The Harris lot size formula identifies the lot size with the smallest inventory and set-up cost per unit as shown in Equation 1 [7].

$$LS = \sqrt{\frac{2\lambda k}{h}} \quad (1)$$

LS = Lot Size
λ = rate of demand

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k = fixed set-up costs (per set-up)
h = inventory costs (per unit and unit time)

The Harris formula has been adapted over the years using dynamic models, most notably by Andler [6]. Recently, Grigutsch et al. developed a model considering the opportunity costs of reduced agility and service degree at high lot sizes, while Schmidt et al. consider half-finished goods and safety stock costs [8][9]. Both models resulted in a decrease in optimal lot size.

Lean manufacturing practices question the validity of a cost-oriented calculation. While economical, large lot sizes cause sluggishness in the production system (long average throughput time) and rigidity (capital lock-up), in turn reducing the return on capital [3].

The every part every interval (EPEI) metric is employed in lean manufacturing to determine the ideal lot size. This metric is also used to gauge the flexibility of a manufacturing process and is defined as time to produce a lot of each variant, as shown in Equation 2 [10].

$$EPEI = \frac{\sum_{1}^{n}(LS \times PT + CO)}{R \times A} \quad (2)$$

LS = Lot Size
PT = Processing Time per unit
CO = Change-over or Set-up Length
R = number of machines working in parallel
n = number of product variants produces on these machines
A = technical availability of the machine

The EPEI value is ideally the interval of new incoming orders, in most cases 1 day, although typical values are frequently higher than 20 days [10].

By assuming the value of 1 day and solving for the lot size, an additional calculation method is defined in Eq. 3.

$$LS = \frac{1\,\text{Day} \times R \times A - n \times CO}{n \times PT} \quad (3)$$

Alternatively, lean practitioners often recommend running the smallest possible lot size for the given capacity by calculating the free time available on every machine and dedicating this time for set-ups, as shown in Equation 4. The lot size then results from the number of set-ups that can be performed in the remaining time per day.

$$LS = \frac{CO \times V}{(WT - V \times PT)} \quad (4)$$

LS = Lot Size [units]
V = Production Volume in time frame [units]
WT = Working Hours in time frame [hours]
PT = Processing Time per unit
CO = Change-over or Set-up Length [hours]

Depending on the number of variants and set-up duration, the two lean approaches (Eq. 2 and 4) generally yield significantly smaller lot sizes than the Harris formula (Eq. 1). Correspondingly, the set-up ratio is larger when using lean approaches [10].

2.2. Modeling Energy Consumption

In manufacturing, energy consumption is calculated as the work of a machine or piece of equipment, estimated as a function of its operating mode. This can be broken down into a resource-attributed portion and a process-dependent portion, as shown in Equation 5 [12,11].

$$W = W_{Resource} + W_{Process} = \sum_{n=1}^{x} P \times T \quad (5)$$

W = Work
n = Operating Mode
x = Number of Operating Modes
P = Power Consumption in Operating Mode
T = Operating Mode duration in investigated time frame

Over the duration of each operating mode, energy consumption is assumed constant. The DFG Ecomation project defines the set of operating modes: WORK, WARMUP WAIT, BLOCK, ERROR, SET-UP, OFF/STANDBY, and SAVE [12]. These modes support the assumption that the majority of energy consumption in manufacturing systems is continuous and deterministic.

The Ecomation project classified energy-consuming equipment in four categories, characterized by their controllability, i.e. their ability to change operating mode under normal factory conditions [11]:

- always on;
- switched on/off commanded by machine control;
- continuous state commanded by machine control; or
- switched on/off or continuously controlled independently.

2.3. Modeling Material Usage

Material waste in machining operations has been modeled in an operating-state dependent manner (e.g. trim-loss in normal operation) or linked to the transition between operating states (e.g. start-up loss), as presented in Alvandi [13]. This method uses either measurement, or the results of more detailed material and process-specific models.

Wear and aging operating materials and operating equipment has also been the subject of intensive simulation, but usually only for specific processes (e.g. cutting) [14].

Inventory deterioration (or shrinkage) represents a portion of factory waste removed from machining operations and has been the subject of extensive modeling in the last 20 years, by assigning a product a shelf-life characteristic. At the meta level, goods are classified as deteriorating or vulnerable to obsolescence, then by their lifetime (fixed or random) and demand structure (stochastic or deterministic) [15].

3. Problem Statement and Approach

After examining the opposing lot-size calculation methods discussed in 2.1, this paper strives to answer the question: *How*